RESPONSE CALIBRATION METHOD USING A FREQUENCY-SHIFTED RECEIVER

Background of the Invention

Many types of measurement and communication systems include a receiver coupled to a signal source through a signal path. Performance of these systems can be limited by amplitude unflatness, group delay variations and other distortion in the receiver or signal path. Calibration schemes, which include determining the frequency response of the receiver or signal path, are used to overcome performance limitations that are attributed to distortion. Known calibration schemes, such as those employed in dynamic signal analyzers, vector signal analyzers and other types of receivers, use the signal source to stimulate the receiver with a known stimulus signal. Response of the receiver to the known stimulus signal is determined and compared to a predicted response to correct for distortion introduced by the receiver. However, when the signal path coupling the source to the receiver introduces distortion to the stimulus signal, the accuracy of this calibration technique relies on both the accuracy with which the stimulus signal is known and the accuracy with which the signal path can be characterized. There is a need for a response calibration method that does not rely on accurately determining the characteristics of the stimulus signal and an accurate characterization of the signal path.

Summary of the Invention

In a response calibration method constructed according to an embodiment of the present invention, a stimulus signal having a non-zero bandwidth is coupled to a receiver through a signal path that introduces distortion to the stimulus signal. The receiver acquires a first digital representation of the stimulus signal at an output of the signal path with the receiver adjusted to a first spectral position. The receiver also acquires a second digital representation of the stimulus signal at the output of the signal path with the receiver adjusted to a second spectral position that is shifted from the first spectral position by a predetermined frequency offset. The frequency response of the receiver when the receiver adjusted to the first spectral position is equated to the frequency response of the receiver when the receiver is adjusted to the second spectral position. A first combined frequency response of the receiver and the signal path is extracted at three or more designated frequencies within the bandwidth of the stimulus signal, and a second combined frequency response of the receiver and signal path is extracted at a set of frequencies offset from the three or more designated frequencies by the predetermined frequency offset. The frequency response of the receiver is determined from the first combined frequency response and the second combined frequency response. The frequency response of the signal path is optionally determined according to the response calibration method under condition that the stimulus signal is known, characterized, designated or otherwise established.

Brief Description of the Drawings

Figure 1 shows an example of a receiver, signal path, and source employing the response calibration method constructed according to an embodiment of the present invention.

Figures 2A-3B show examples of stimulus signals and frequency responses of the receiver and the signal path included in the response calibration method constructed according to the embodiment of the present invention.

Figure 4 is a flow diagram of the response calibration method constructed according to the embodiment of the present invention.

Detailed Description of the Embodiments

Figure 1 shows an example of a receiver 12, a source 14, a signal path 16 and a processor 18 employing the response calibration method constructed according to an embodiment of the present invention. The frequency response of the receiver 12 is determined according to the response calibration method. From the determined frequency response of the receiver 12, a time domain impulse response, or any other response suitable for calibrating the receiver 12 can be determined using the known mappings between the frequency domain and the time domain.

The source 14 provides a stimulus signal S(f) that has non-zero bandwidth. The stimulus signal S(f) has a continuous spectrum as shown in Figures 2A and 2B. Alternatively, the stimulus signal S(f) has a discrete spectrum as shown in Figures 3A and 3B, where the stimulus signal S(f) is a frequency comb with discrete teeth separated by a frequency spacing Δ.

Through the signal path 16, the stimulus signal S(f) is coupled to the receiver 12. The signal path 16 has an input I coupled to the source 14 and an output O coupled to the receiver 12. The signal path 16 is typically a mixer or other active element, a transmission line, filter or other

passive element, or combination of active and passive elements having a frequency response H(f). Typically, the signal path 16 modifies the amplitude and/or the phase of the stimulus signal S(f) between the input I and the output O of the signal path 16. The frequency response H(f) of the signal path 16 is optionally determined according to the response calibration scheme under condition that the stimulus signal S(f) is known, characterized, designated or otherwise established.

The receiver 12 is a dynamic signal analyzer, vector signal analyzer, heterodyne system or other frequency translating or shifting system, and has a frequency response G(f). The frequency response G(f) of the receiver 12 has the characteristic that the relative amplitudes and relative phases of the frequency response G(f) remain fixed whether the receiver 12 is in a first spectral position F_{C1} or in a second spectral position F_{C2} resulting in the receiver response G'(f). The receiver 12 intercepts the stimulus signal S(f) at the output of the signal path 16 and acquires a first digital representation Y1(f) of the stimulus signal at the output O of the signal path 16 with the receiver 12 adjusted to the first spectral position F_{C1}. The first digital representation Y1(f) is a product expressed in equation 1.

(1) $$Y1(f) = S(f)H(f)G(f).$$

The receiver 12 intercepts the stimulus signal S(f) at the output of the signal path 16 and acquires a second digital representation Y2(f) of the stimulus signal at the output O of the signal path 16 with the receiver 12 adjusted to the second spectral position F_{C2} that is frequency-shifted from the first spectral position F_{C1} by a frequency offset δ. The second digital representation is a product expressed in equation 2.

(2) $$Y2(f) = S(f)H(f)G'(f).$$

In equation 2, the frequency-shifted frequency response G'(f) of the receiver 12 represents the frequency response G(f) of the receiver 12 shifted by the frequency offset δ. Thus, $G'(f+\delta)=G(f)$, indicating that the second spectral position F_{C2} is at a higher frequency than the first spectral position F_{C1} as shown in Figures 2A-3B.

In Figure 1, the processor 18 is coupled to the receiver 12. Typically, the processor 18 is a microprocessor or computer that is either incorporated within the receiver 12, or that is external to the receiver 12. The processor 18 extracts a first combined frequency response $X1_k$ of the receiver 12 and the signal path 16 at at least three designated frequencies f_k within the bandwidth of the stimulus signal S(f). This first combined frequency response $X1_k = H(f_k)G(f_k)$, where k = 0, 1, 2...N-1, an integer indexing each of the designated frequencies f_k .

The first combined frequency response $X1_k$ is obtained by normalizing the first digital representation $Y1(f_k)$ by the stimulus signal S(f) at the three or more designated frequencies f_k . According to the normalization, $X1_k = Y1(f_k)/S(f_k)$, where $S(f_k)$ represents the stimulus signal S(f) at the designated frequencies f_k . Alternatively, the first combined frequency response $X1_k$ is obtained by adaptive filtering to obtain a combined impulse response of the signal path 16 and the receiver 12. Mapping this combined impulse response into the frequency domain provides the first combined frequency response $X1_k$ at the three or more designated frequencies f_k.

The processor 18 extracts a second combined frequency response $X2_k$ of the receiver 12 and the signal path 16 at a set of frequencies offset from the three or more designated frequencies f_k by the frequency offset δ. This second combined frequency response $X2_k = H(f_{k+1})G'(f_{k+1})$, where k = 0, 1, 2...N-1, where $G'(f_{k+1})=G(f_k)$, indicating that the second spectral position F_{C2} is at a higher frequency than the first spectral position F_{C1}.

The second combined frequency response $X2_k$ is obtained by normalizing the second digital representation Y2(f) by the stimulus signal S(f) at the set of frequencies designated as f_{k+1}. According to the normalization, $X2_k = Y2(f_{k+1})/S(f_{k+1})$. Alternatively, the second combined frequency response $X2_k$ is obtained by adaptive filtering to obtain the impulse response of the signal path 16 and the receiver 12. Mapping the obtained impulse response to the frequency domain provides the second combined frequency response $X2_k$ at the set of frequencies f_{k+1}. In addition to using normalization or adaptive filtering to extract the combined frequency responses $X1_k$ and $X2_k$, cross-correlation, cross spectrum analysis, adaptive channel modeling and other known techniques are alternatively used to extract the combined frequency responses $X1_k$ and $X2_k$.

The number and the spacing of the designated frequencies f_k are chosen so the frequency response G(f) of the receiver 12 is determined to a specified accuracy. The accuracy to which the frequency response G(f) is determined generally increases as the number of designated frequencies f_k increases and as the spacing of the designated frequencies f_k decreases. In an example where the stimulus signal S(f) is a frequency comb, the frequency offset δ between the first spectral position F_{C1} and the second spectral position F_{C2} is chosen to be equal to the frequency spacing Δ of the teeth of the frequency comb. Alternatively, when the frequency offset δ is not equal to the frequency spacing Δ, interpolation is used to acquire the first combined frequency response $X1_k$ and the second combined frequency response $X2_k$.

The processor 18 equates the frequency response G(f) of the receiver 12 to the frequency response G'(f) of the receiver 12, where the frequency response G'(f) is shifted from the frequency response G(f) by the frequency offset δ. This corresponds to the shifting of the frequency response of the receiver 12 from the first spectral position F_{C1} to the second spectral

position F_{C2}. Figures 2B and 3B show the frequency response G(f) shifted between the first spectral position F_{C1} and the second spectral position F_{C2}, resulting in the frequency response G'(f). According to this frequency shifting, $G(F_{L1}+k\delta)=G'(F_{L2}+k\delta)=G(F_{L2}+(k-1)\delta)$ where F_{L1} represents a lower spectral bandwidth position when the receiver 12 is in the first spectral position F_{C1} and where F_{L2} represents a lower spectral bandwidth position when the receiver 12 is in the second spectral position F_{C2}. In the first spectral position F_{C1}, shown in Figure 2A and Figure 3A, the receiver response G(f) has a spectral bandwidth that extends from F_{L1} to F_{U1}. In the second spectral position F_{C2}, shown in Figure 2B and Figure 3B, the receiver response G'(f) has a spectral bandwidth that extends from F_{L2} to F_{U2}. The non-zero bandwidth of the stimulus signal S(f) extends at least as broad as the frequency range from F_{L1} to F_{U2}. Generally, the responses of the signal path 16 and the receiver 12, and the stimulus signal are vector quantities having magnitude and phase components. Figures 2A-2B show the magnitude components versus frequency.

The processor 18 then determines the frequency response G(f) of the receiver 12 and the frequency response H(f) of the signal path 16 at frequencies f_k from the extracted first combined response $X1_k$ and the extracted second combined frequency response $X2_k$. A time domain impulse response, or any other response suitable for calibrating the receiver 12 is optionally derived from the frequency response G(f), based on known mappings between the frequency domain and the time domain. The frequency response G(f) of the receiver 12 is determined according to equation 3 and equation 4. The frequency response H(f) of the signal path 16 is optionally determined according to equation 3 and equation 4.

(3) $$X1_k = G_k H_k$$

(4) $$X2_k = G_k H_{k+1}$$

where $G_k=G(f_k)$, and $H_k=H(f_k)$.

Table 1A shows correspondence between the three or more designated frequencies f_k, the extracted first combined frequency responses $X1_k$, the frequency response H_k of the signal path 16 and the frequency response G_k of the receiver 12 in the example where three frequencies f_k have been designated. Table 1B shows correspondence between the set of frequencies f_{k+1}, the extracted second combined frequency responses $X2_k$, the frequency response H_{k+1} of the signal path 16 and the frequency response G_k of the receiver 12 in the example where there are three designated frequencies f_k.

TABLE 1A

f_0:	$X1_0$	G_0	H_0
f_1:	$X1_1$	G_1	H_1
f_2:	$X1_2$	G_2	H_2

TABLE 1B

f_1:	$X2_0$	G_0	H_1
f_2:	$X2_1$	G_1	H_2
f_3:	$X2_2$	G_2	H_3

The application of equation 3 and equation 4 provides the frequency response G_k of the receiver 12 at the designated frequencies f_k. First, an initial designation for the frequency response of the signal path 16 is made at one of the frequencies f_0 - f_N. For example, the initial designation is made for the frequency response H_0 of the signal path 16 at the first of the designated frequencies f_0. Using the extracted first combined frequency response $X1_0$ at frequency f_0, the frequency response G_0 of the receiver 12 at frequency f_0 is determined according to equation 3 as $X1_0/H_0$. Using the extracted second combined frequency response $X2_0$ at frequency f_1 and substituting the determined frequency response G_0 into equation 4 provides that the frequency response H_1 of the signal path 16 at frequency f_1 equals $X2_0/G_0$. Using the extracted first combined frequency response $X1_1$ at frequency f_1 and substituting H_1 into equation

3 provides that the frequency response G_1 of the receiver 12 at frequency f_1 equals $X1_1/H_1$. Using the extracted second combined frequency response $X2_1$ at frequency f_2 and substituting G_1 into equation 4 provides that the frequency response H_2 of the signal path 16 at frequency f_2 equals $X2_1/G_1$. Using the extracted first combined frequency response $X1_2$ at frequency f_2 and substituting H_2 into equation 3 provides that the frequency response G_2 of the receiver 12 at frequency f_2 equals $X1_2/H_2$. Using the extracted second combined frequency response $X2_2$ at frequency f_3 and substituting G_2 into equation 4 provides that the frequency response H_3 of the signal path 16 at frequency f_3 equals $X2_2/G_2$.

In this example, the designated frequencies $f_0...f_3$ are used to illustrate the application of equation 3 and equation 4 to determine the frequency response G_k. When there are more than three designated frequencies f_k, the initial designation of the frequency response of the signal path 16 at one of the frequencies f_0 - f_N and the similar application of equation 3 and equation 4 are used to determine the frequency response G_k. Once the frequency response G_k of the receiver 12 is determined, the receiver 12 can be calibrated by compensating for amplitude unflatness, group delay variations and other distortion in the receiver 12, that in the absence of calibration, can limit the performance of the receiver 12.

Under condition that the stimulus signal S(f) is known, characterized, designated or otherwise established at the designated frequencies f_0 - f_N, the frequency response H_0 - H_N, determined through the application of equation 3 and equation 4, accurately represents the frequency response of the signal path 16. A time domain impulse response, or any other response suitable for calibrating the signal path 16 is optionally derived from the frequency response H_k of the signal path 16, based on known mappings between the frequency domain and the time domain. Thus, the response of the signal path 16 is optionally determined according to the

response calibration scheme. Once the response of the signal path 16 is determined, the signal path 16 can be calibrated by compensating for amplitude unflatness, group delay variations and other distortion in the signal path 16.

Figure 4 is a flow diagram of the response calibration method 20 constructed according to the embodiment of the present invention. In step 21 of the method 20, the stimulus signal S(f) having non-zero bandwidth is coupled to the receiver 12 through the signal path 16. In step 22, the receiver 12 acquires the first digital representation Y1(f) of the stimulus signal at the output O of the signal path 16 with the receiver 12 in a first spectral position F_{C1}. In step 23, the receiver 12 acquires the second digital representation Y2(f) of the stimulus signal at the output O of the signal path 16 with the receiver 12 in a second spectral position F_{C2} shifted from the first spectral position F_{C1} by the predetermined frequency offset δ. In step 24, the frequency response G(f) of the receiver 12 when the receiver 12 is in the first spectral position F_{C1} is equated to the frequency response G'(f) of the receiver 12 when the receiver 12 is frequency-shifted to the second spectral position F_{C2}.

In step 25, the first combined frequency response $X1_k$ of the receiver 12 and the signal path 16 is extracted at at least three designated frequencies f_k within the bandwidth of the stimulus signal S(f). Extracting the first combined frequency response $X1_k$ of the receiver 12 and the signal path 16 at the at least three designated frequencies f_k includes normalizing the first digital representation Y1(f) by the stimulus signal at the at least three predesignated frequencies f_k.

In step 26, the second combined frequency response $X2_k$ of the receiver 12 and signal path 16 is extracted at the set of frequencies f_{k+1} within the bandwidth of the stimulus signal S(f). Extracting the second combined frequency response $X2_k$ of the receiver 12 and the signal path

16 the set of frequencies f_{k+1} includes normalizing the second digital representation Y2(f) by the stimulus signal S(f) at the set of frequencies f_{k+1}. In addition to using normalization to extract the combined frequency responses $X1_k$ and $X2_k$, adaptive filtering, cross-correlation, cross spectrum analysis, adaptive channel modeling and other known techniques are alternatively used to extract the combined frequency responses $X1_k$ and $X2_k$.

In step 27, the frequency response of the receiver 12 is determined from the first combined frequency response $X1_k$ and the second combined frequency response $X2_k$. Determining the frequency response G_k of the receiver 12 from the first combined frequency response $X1_k$ and the second combined frequency response $X2_k$ includes designating a response of the signal path 16 at a predetermined one of the at least three designated frequencies f_0 - f_N within the bandwidth of the stimulus signal and solving for the frequency response G_k of the receiver 12 according to equation 3 and equation 4.

Under condition that the stimulus signal S(f) is known, characterized, designated or otherwise established at the frequencies f_0 - f_N, the frequency response H_0 - H_N , determined through the application of equation 3 and equation 4, accurately represents the frequency response of the signal path 16. Thus, the frequency response of the signal path is optionally determined through the application of equation 3 and equation 4 as shown in step 28. A time domain impulse response, or any other response suitable for calibrating the receiver 12 is optionally derived from the frequency response of the signal path 16, based on known mappings between the frequency domain and the time domain.

While the embodiment of the present invention has been illustrated in detail, it should be apparent that modifications and adaptations to this embodiment may occur to one skilled in the art without departing from the scope of the present invention as set forth in the following claims.